PROTON FLUENCE PREDICTION MODELS

Joan Feynman

Jet Propulsion Laboratory, California Institute of Technology,

Pasadena, California, 91109, U. S. A.

Abstract

Many spacecraft anomalies are caused by positively charged high energy particles impinging on the vehicle and its component parts. Here we review the current knowledge of the interplanetary particle environment in the energy ranges that are most important for these effects, 10to 100 MeV/amu. The emphasis is on the particle environment at 1 AU. State-of-the-art engineering models are briefly described along with comments on the future work required in this field.

Introduction

The problem of predicting hazardous environments for spacecraft is complicated by the fact that there are many different ways in which a device in space can be effected by energetic particles. For example, degradation of electronic parts and power 10ss in solar cells is related to the total dose of ionizing radiation the part receives over its lifetime. However, another type of damage is due to the effects caused by a single ion depositing energy in a sensitive volume of the instrument (Single Event Effects). For still other types of damage the quantity of importance is the value of the peak particle flux. The first step in the evaluation of the environment then, is to identify the type of damage of concern and the parameters Of importance for that effect; protons or ions, high energy or low, total flux (fluence) 01 peak flux. In principle, the techniques of predicting each of these quantities differ.

Energetic particles come from two main sources, galactic cosmic Jays and solar events. The two types of particles are discussed separately.

Galactic Cosmic Rays

Galactic cosmic rays arc present at all times and the major change in the fluxes and fluences is an 11 year solar cycle. They are high energy nuclei propagating throughout the heliosphere with a flux that is almost completely isotropic but is solar cycle dependent. There is a decrease (increase) in cosmic ray intensity near solar maximum (minimum). This is reflected in the neutron monitor counting rate data shown in Figure 1. A second source of solar cycle variation is the "anomalous component" of the cosmic rays. These particles arc helium and heavier ions that have energies less than -50 MeV/nuc. They are seen at 1 Au only during solar minimum and the details differ from minimum to minimum (Mewaldt et al., 1993).

Proton events

While the cosmic rays provide an essentially steady background of high energy particles, particles due to solar events dominate the environment for energies from 1 to 100 MeV/amu. Proton fluxes have been observed in space from 1963 to the present and it has been found that solar energetic particle events are very sporadic. However, the data set has now been collected over a long enough time period to permit a good statistical sample of proton events to be assembled (Armstrong et al., 1983; see also Feynman et al., 1993). Proton fluences (i.e. proton fluxes integrated over a period of increased flux) observed in an event can vary from just above the cosmic ray background to very high fluences. For example, > 10^{10} protons/cm^2 were observed at energies above 10 MeV during an event in October 1989 (Feynman et al., 1993). Event fluences above 1.5 x 10^9 protons/cm^2 (E>10 MeV) are very rare and only about 13 of them have occurred since 1963. No events with E>10 MeV fluences >10^{10} protons/cm^2 occurred between the famous event of August 1972 and the October 1989 event, a period of 17 years. The 1972 event and its associated geomagnetic storm caused widespread power outages in Canada and the United States and alerted the public to the importance of major solar proton events. But the 17 year hiatus led to the impression that the 1972 event was of a different class from all other proton enhancements (King, 1974) and that this different class was very rare. However, major events had been observed before 1963 (Malitson and Webber, 1962; Feynman et al., 1990) and have appeared again in both 1989 and 1991. Major events appear to be the high fluence end of a smooth distribution of particle fluences (Feynman et al. 1990). This smooth distribution of fluences is in marked contrast to the distribution of peak fluxes discussed by Smart and Shea (this conference,(x)). Care must be taken to use fluence models for estimating hazards due to integrated doses and to use peak flux models for effects dependent on that quantity.

Solar particle events are clearly associated with events taking place on the Sun. There is, however, currently a major controversy as to whether the particle acceleration takes place in the flare itself or the particles are accelerated by associated coronal mass ejections (CMEs) (See Gosling, 1993 and references therein.)

in any case it has become evident that there are two different types of solar X-ray flares, gradual and impulsive. There is increasing evidence that these different types of solar events are associated with different types of particle events in the energy range above 5 MeV (Reames, 1994), Figure 2 contrasts x ray events seen during two days in May 1992. The impulsive event on May 3 shows both a rapid increase and a rapid decrease in x-ray flux. In gradual events, such as that on May 8, the decay of the X-ray intensity takes place over many hours. The two classes are no always as easily distinguishable as those in Figure 2.

Gradual events, often called LDE (Long Duration Events), are strongly associated with CMEs and tend to be the events with the largest proton fluences and the highest proton peak fluxes. They have elemental abundances and isotopic compositions that are characteristic of coronal regions having an electron temperature of 1 to 2 MK (million degrees Kelvin) (Reames et al., 1990). The largest solar proton fluence events often occur in association with a series of major gradual flares from a single active region as it is carried across the face of the Sun (Malitson and Webber, 1962, Feynman et al. 1993). It is widely believed these particles are accelerated by CME driven shocks in the corona and lower solar wind (c. f. Gosling, 1993), Figure 3 shows a major proton event associated with a series of high velocity CMEs (Feynman and Hundhausen, 1994, Feynman, 1996). If a CME velocity is supersonic with respect to the ambient solar wind, a shock will form and particle acceleration will take place. Figure 4 shows the velocities of almost 1,000 CMEs observed by the High Altitude Observatory (NCAR) coronagraph on the Solar Maximum Mission (Burkepile and St.Cyr, 1993). Over half the events have velocities too low to form a shock. Figure 5 shows the. distance from the Sun at which CMEs of a given velocity become supersonic when propagating into an average ambient solar wind. Note that for a CME velocity of 700 Km/see the shock forms after the CME is at more than 5 solar radii, This emphasizes the fact that the vast majority of CMEs seen in coronagraph images have no shock. The increase in density that is such a prominent and dramatic feature of CME images is the CME material itself. The image does not show either the shock or the compressed ambient solar wind in the region between the shock and the CME. At Earth the shock, the compressed ambient solar wind and the CME material itself all are evident in the solar wind observations (Hirshberg et al. 1970). The number of CMEs/year producing shocks near the Sun can be estimated from comparing figures 4 and 5. We find that 15 or 20 CMEs fast enough to form a particle accelerating shock were observed per year. CMEs can be observed by coronagraphs if they occur within 30 degrees of either limb of the Sun so the observations shown represent "120 degrees of' solar longitude. The longitudinal extent of the region from which solar protons can reach the Earth is perhaps 200 degrees (particle enhancements are caused by events taking place on the visible disk and also are often attributed to events taking place on the far side of the Sun within 30 degrees of the west limb). Thus the estimated number of shock producing CMEs that may produce proton enhancements at Earth is 25 to 30 per year during the active period of the solar cycle (see below). After the particles are accelerated, they propagate to the Earth either directly along the magnetic field connecting to the acceleration region, or after many scatterings. The particle distribution at Earth is primarily isotropic, which indicates repeated scattering.

The other type of solar event, impulsive events, produce energetic particle fluences with marked enhancements of heavy ions. These events are generally dominated by electron fluxes and have smaller proton fluxes than the gradual events. These electrons do not cause spacecraft charging and do not represent any significant hazard to spacecraft. Studies of the Composition indicate that the ions are from regions of the corona having electron temperatures of 3-5 MK (Reames, 1994).

A Proton Fluence Model

An important use of particle fluence predictions is in the definition of a radiation environment for spacecraft system design. The sunspot number is often used as a back-of-the-envelope guide as to the expected severity of the particle environment. However, that is not a valid approach, even for a first guess (Feynman et al., 1990). Thirty years of experience have shown that the proton fluence to be expected per year is not proportional to the sunspot number in that year or the maximum sunspot number of that cycle (figure 6). The important parameter appears to be, not the sunspot number, but the phase of the sunspot cycle. Figure 7 shows the total integrated yearly fluence for 12 month periods (years relative to the sunspot maximum month) from 1956 through 1985. The cycle can be divided into active and quiet periods. During the quiet period the risk from proton events is minimal. The active period is the 7 years beginning 2 years before maximum and lasting until 4 years after maximum. Even in the active period there is a factor of 100 difference in fluence among the cycles, in estimating fluences for a mission, only the number of active years need be taken into account.

A predictive model for proton fluences, called JPL 1991, has been developed using data from 1963 through April of 1991 (Feynman et al., 1993). Several very large proton events have occurred since the model was constructed, particularly in the later months of 1991, However, predictions made by the published model were not changed significantly by the inclusion of these later events. The JPL1991 model apparently is based on a data set collected over a long enough time that it is quite stable. For a complete description of the model see Feynman et al, (1993), Here only a brief description is given.

The data set contains hourly values of the fluences collected in space by the OGO series of spacecraft. As illustrated in figure 3 major proton events are usually composed of a series of increases associated with a series of CMEs or flares from a single active region as it is carried across the face of the Sun. To take account of this effect we define a proton "event" by defining a threshold value for the daily fluence. We then integrate the daily fluences starting with the first day on which the fluence exceeds the threshold and ending when the fluence is below the threshold for more than one day. Using the list of events defined in this way, we arrange the data in order of event integrated fluence. For each event we then plot the size of the fluence versus the percent of events in the data set that have a fluence less than that size. For example, if we had a data set containing 100 events, the graph would show the log of the magnitude on the ordinate and 99% on the abscissa, since 99 of the 100 events have a fluence less than the largest fluence. The median fluence would be plotted at 50%. Figure 8 shows the resultant plot for particle energies >10 MeV during the active part of the solar cycle.

in figure 8 the abscissa has been ruled so that if the magnitudes of the events had a Gaussian distribution, the points would appear along a straight line. Obviously the distribution is not Gaussian. However, the distribution is so steep at the high fluence end that the total fluence experienced in a mission will be determined by the number of very large events, if any occur. Because of this it is only important to predict the large events accurately. To do this a Gaussian is used that fits the largest events well, as shown in the figure 8. This Gaussian is then used in Monte Carlo calculations of fluences for various mission lengths. See Feynman et al. (1993). Figure 9 shows the probability of exceeding a given fluence for several different mission lengths for energy >10 MeV. This figure may be used directly for missions at 1 AU. No other computer modeling is needed. Simply count the number of years the mission will fly during the active part of the solar cycle defined in figure 7, decide on the probability desired and read the fluence from figure 9. For mission lengths longer than the 7 active years, assume that no fluence will be collected during the quiet solar period and add the fluence for the additional active years.

Problem areas for future work

Although we can make a statistical prediction of the mission integrated fluences of protons at 1 AU, the situation is less than satisfactory for other important parameters. For example, no models exist for the prediction of peak fluxes, although the peak flux distribution presented at this meeting (Smart and Shea, 1996) is an advance towards that goal. This is an important parameter for many devices in space and should be the focus of a modeling study.

Other very important parameters include the fluxes and fluences of heavy ions. Ideally the best method would be to use the measured ion fluxes and construct a model based on that data. However, the ion fluences are difficult to measure. Thus no data set exists that covers a long enough time period with sufficient accuracy to make such a model feasible. Instead, the usual procedure is to calculate the proton fluence and estimate the ion fluence from some estimate of the ion/proton ratio. But the ion/proton ratio varies strongly from event to event. Sometimes a "double worst case" scenario is used in which a major proton event fluence is assumed to have an ion enriched composition. However, as pointed out above, major proton events are associated with gradual solar events whereas ion enrichments are associated with impulsive events. There is no known case in which a major proton event exhibits an enriched composition. A more realistic procedure would be to use fluences from major proton events with the ion/proton ratios measured in major events. A second approach that has been suggested is based on the observation that the ion/helium ratio does not vary from event to event as strongly as does the ion/proton ratio. Helium is more easily detected than heavy ions so that a better helium data set exists. It has been suggested that a model of the helium fluence be constructed using the same techniques as have been used for the protons. The ion/helium ratio would then permit a more reliable estimate of the expected heavy ion environment.

For space missions that are not confined to 1 AU the question of" the heliocentric radial gradient of the fluxes and fluences becomes very important. It has been suggested that the largest observed values of peak flux are due to the interaction of already accelerated particles with shocks in space (cf. Shea and Smart 1990). Work should be done to verify this concept. Event integrated fluences pose a different problem. The radial gradient will depend on the method by which these particles are accelerated, particularly whether they are accelerated in flares at the Sun, by CME shocks in the near-Sun region, or by shocks throughout the heliosphere. Further fundamental studies and modeling of the proposed acceleration processes are needed before the radial gradients can be understood well enough to make reliable estimates of the expected radiation environment in space.

Acknowledgments: I thank Dr. S. B. Gabriel for interesting discussions and Dr. B. G. Goldstein for calculations of the heliocentric shock distances. This research was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Figure Captions:

Figure 1. Solar cycle variation of the sunspot number and of neutron monitor counting rates (McKibben, 1988). The counting rates are indicative of the fluences of high energy galactic cosmic rays and increase with increasing cosmic ray flux

Figure 2. X-ray events seen during two days in May 1992, showing the contrast between gradual and impulsive events (data from Solar and Geophysical Data, NES, NOAA, 1992).

Figure 3. The major proton event of March 1989. This event was associated with a series of high velocity CMEs (data from Solar and Geophysical Data, NES, NOAA, 1989).

Figure 4. Velocities of almost 1,000 CMEs observed by the High Altitude observatory (NCAR) coronagraph on the Solar Maximum Mission (Burkepile and St. Cyr, 1993). The last bin contains all CMEs with velocities greater than 1,200 km/sec.

Figure 5. The distance from the Sun at which CMEs of a given velocity become supersonic when propagating into an average ambient solar wind.

Figure 6. The proton fluence per 12 month period vs. the sunspot number during the same period, showing that these quantities are not proportional.

Figure 7. The total integrated yearly fluence for 12 month periods (years relative to sunspot maximum) from 1956 through 1985.

Figure 8. Distribution of event fluences for particle energies >10 MeV during the active part of the solar cycle. The straight line is a Gaussian fit to the distribution of the large fluence events.

Figure 9. The probability of exceeding a given fluence for several different mission lengths for energy >10 MeV.

References:

Armstrong, T. P., C. Brungardt and J. E. Meyer, Satellite observations of interplanetary and polar cap solar particle fluxes from 1963 to the present, Weather and Climate Responses to Solar Variations, Billy M McCormac, Ed. Colorado University Press, 1983.

Burkepile, J. T. and O. C. St.Cyr, A revised and expanded catalogue of mass ejections observed by the Solar Maximum Mission Coronagraph, NCAR/TN-369+STR, NCAR, Boulder Colo., 1993.

Feynman, J., T. P. Armstrong, L. Dao-Gibner, and S. M Silverman, Solar proton events during solar cycles 19, 20, and 21, Solar Physics, 126, 385, 1990.

Feynman, J, G. Spitale, J. Wang and S. Gabriel Interplanetary proton fluence model : JPL 1991, J. Geophys. Res., 98, 13281, 1993.

Feynman J. and A. J. Hundhausen, Coronal mass ejections and major solar flares: the great active center of March 1989, J. Geophys. Res. 99, 8451, 1994.

Feynman, J. Coronal Mass Ejections and Solar Proton Events During the Great March 1989 Disturbances, submitted J. Geophys Res., 1996.

Gosling, J. T., The Solar Flare Myth, J. Geophys. Res., 98, 18,937, 1993.

Hirshberg, J., A, Alksne, D. S. Colburn. S J. Bame, and A .J. Hundhausen, Observation of a solar flare induced interplanetary shock and helium enriched driver gas, J. Geophys. Res., 75, 1,1970.

King, J. H., Solar proton fluences for 1977-1983 space missions, Journal of Spacecraft and Rockets, 11, 401, 1974.

Malitson, H. H. and W. R. Webber, A summary of cosmic ray events, in Solar Proton Manual, Frank B. McDonald ed.. NASA Goddard Space Flight Center, X-611-62-122, Greenbelt MD, 1962.

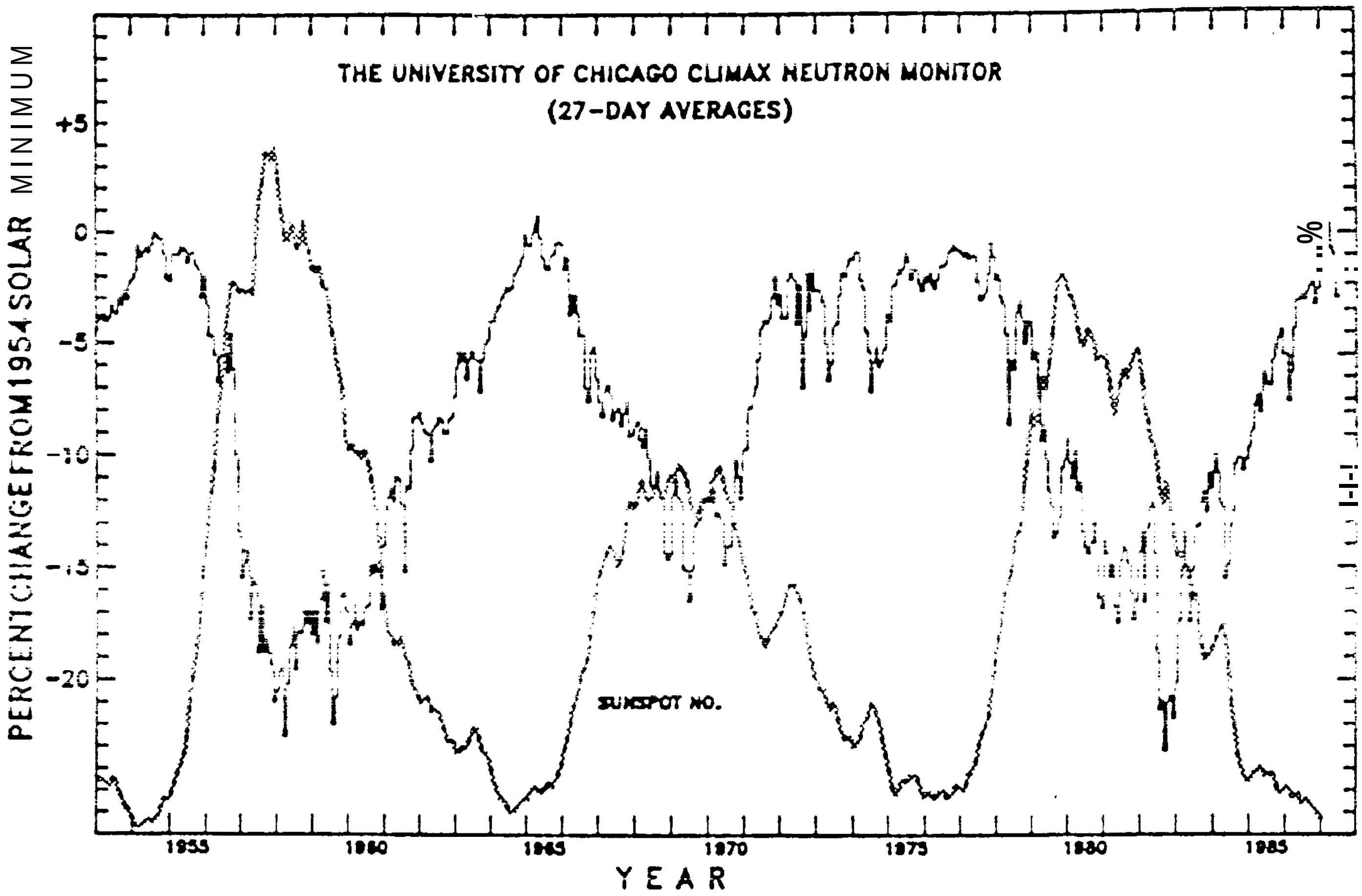
McKibben, R. B. Gradients of galactic cosmic rays and anomalous components, 135, in Interplanetary Particle Environment, J Feynman and S. Gabriel, Eds, JPL Publication 88-28,1988.

Mewaldt, R. A., A. C. Cummings, J R. Cummings, E C. Stone, B. Klecker, D. Hovestadt, M. Scholer, G. M Mason, J. E. Mazur, D. C. Hamilton, T. T. von Rosenvinge, J. B. Blake, The return of the anomalous cosmic rays to 1AU in 1992, Geophys. Res. Lttrs. 20, 2263, 1993

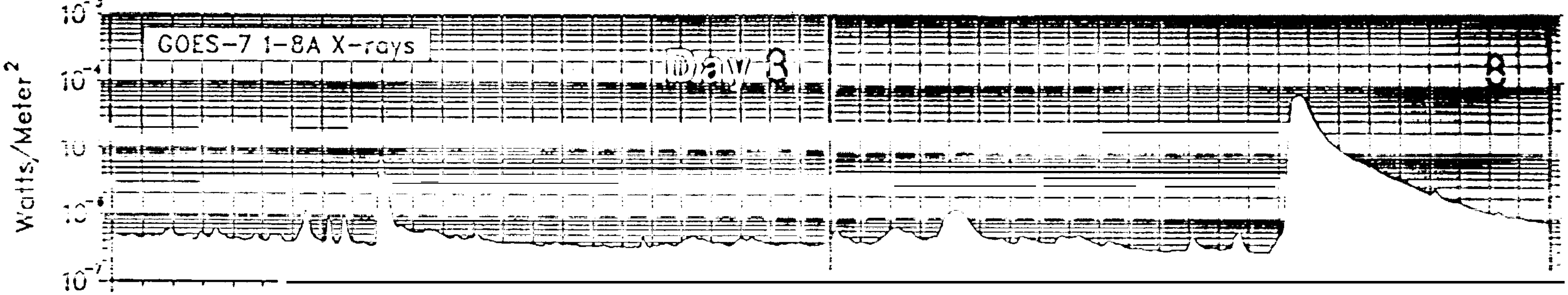
Reames, D. V., J. P. Meyer and T. T. von Rosenvinge, Energetic-Particle abundances in impulsive flare events, Ap. J, Supl. 90, 649-667, 1994.

Shea, M. A, and D. F. Smart, A summary of major solar proton events, Solar Physics, 127, 297, 1990.

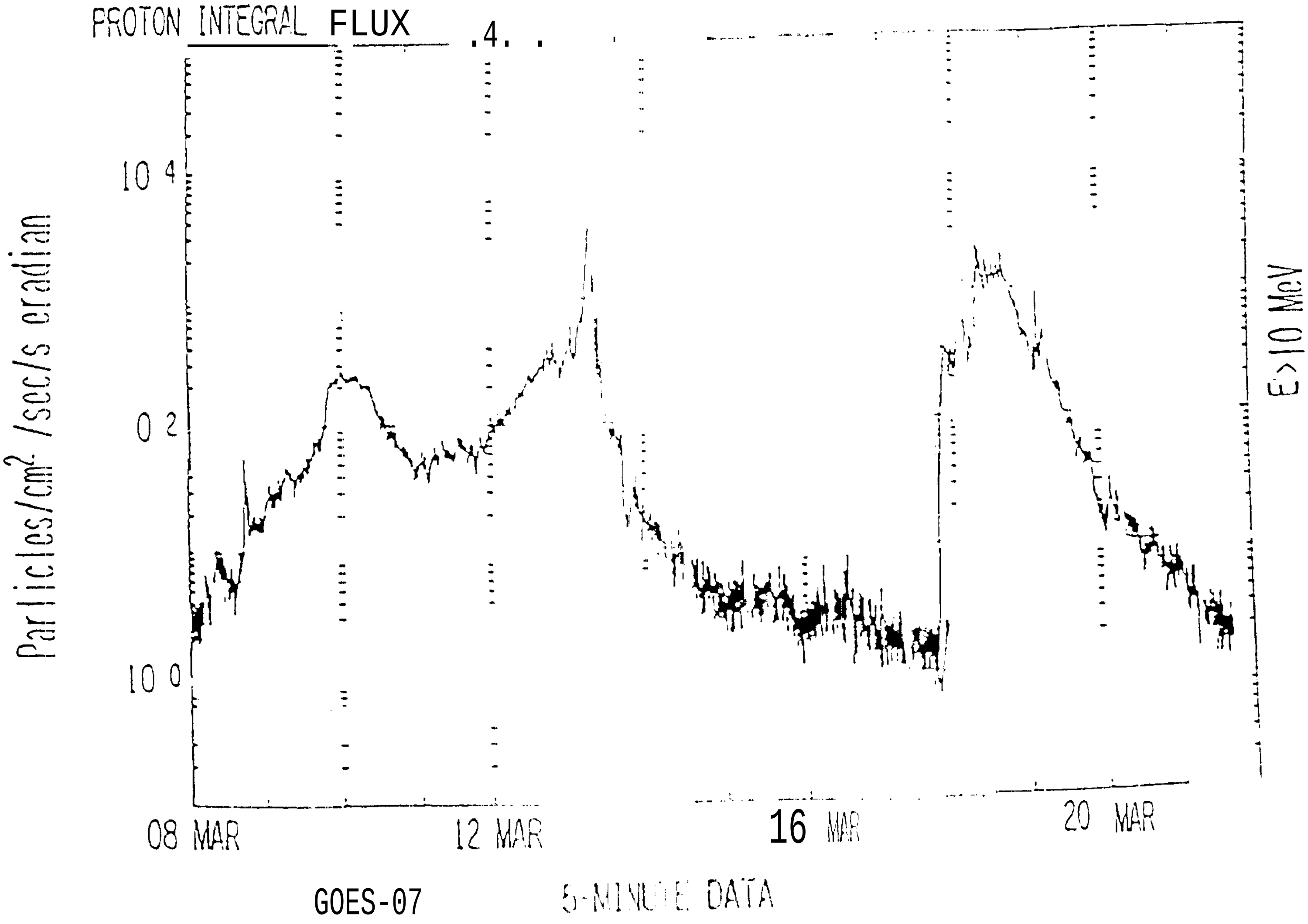
Smart, D. F. and M. A. Shea, The >10 MeV solar proton event peak flux distribution, This conference, 1996.

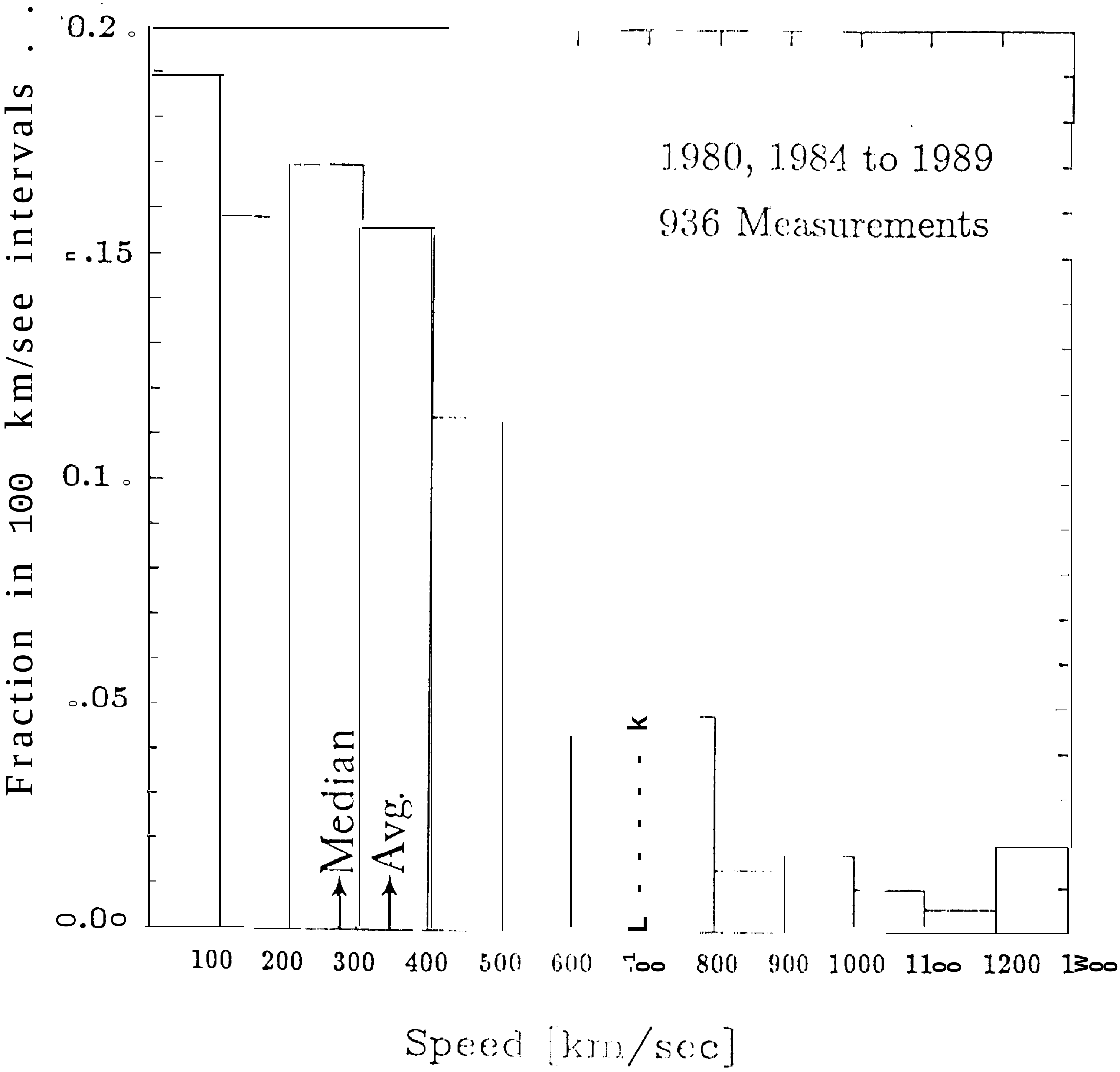

THE UNIVERSITY OF CHICAGO CLIMAX NEUTRON MONITOR
(27-DAY AVERAGES)
PERCENT CHANGE FROM 1954 SOLAR MINIMUM
+5
0
-5
-10
-15
-20
SUNSPOT NO.
1955
1960
1965
1970
1975
1980
1985
YEAR
%

SOLAR-TERRESTRIAL ENVIRONMENT
May 1992

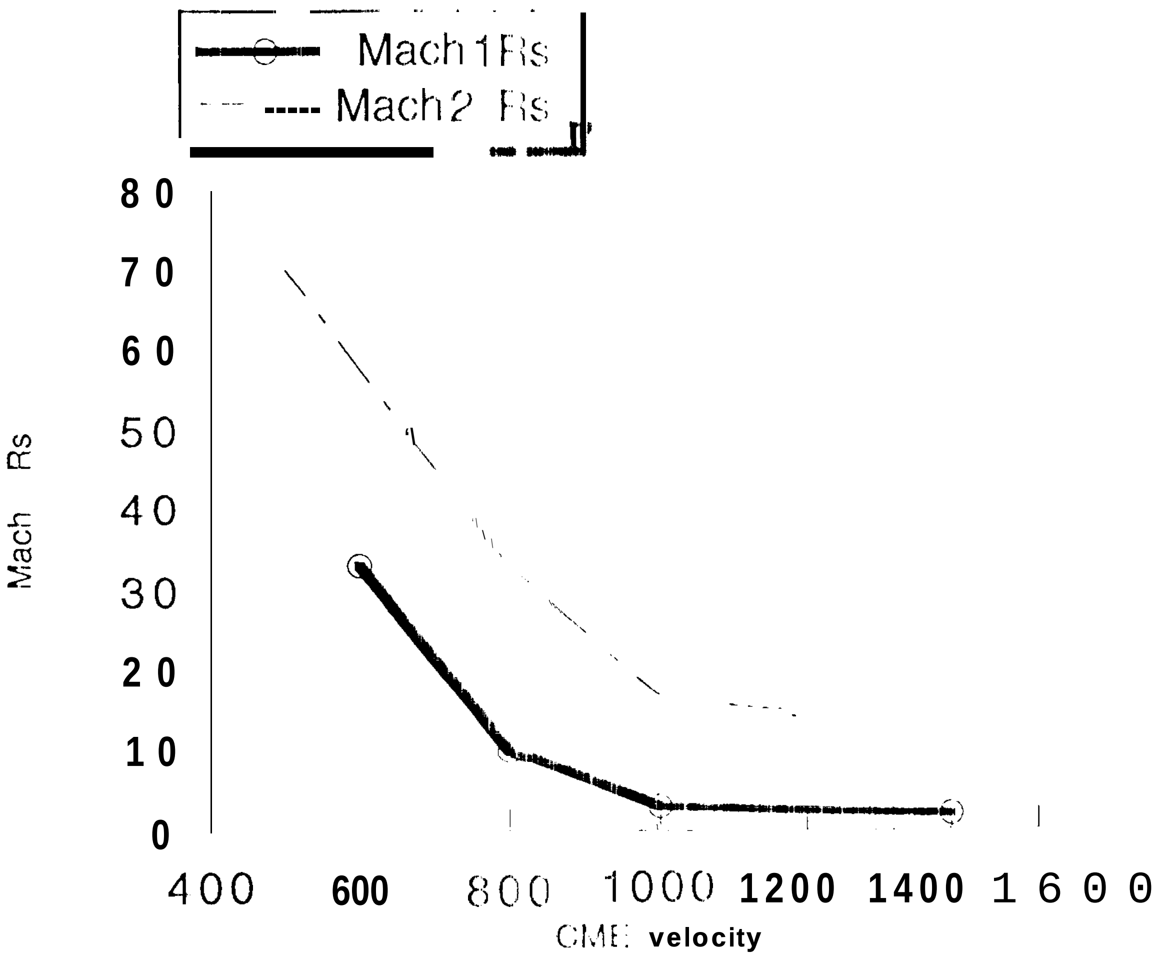


Interplanetary Proton Event, March, 1989

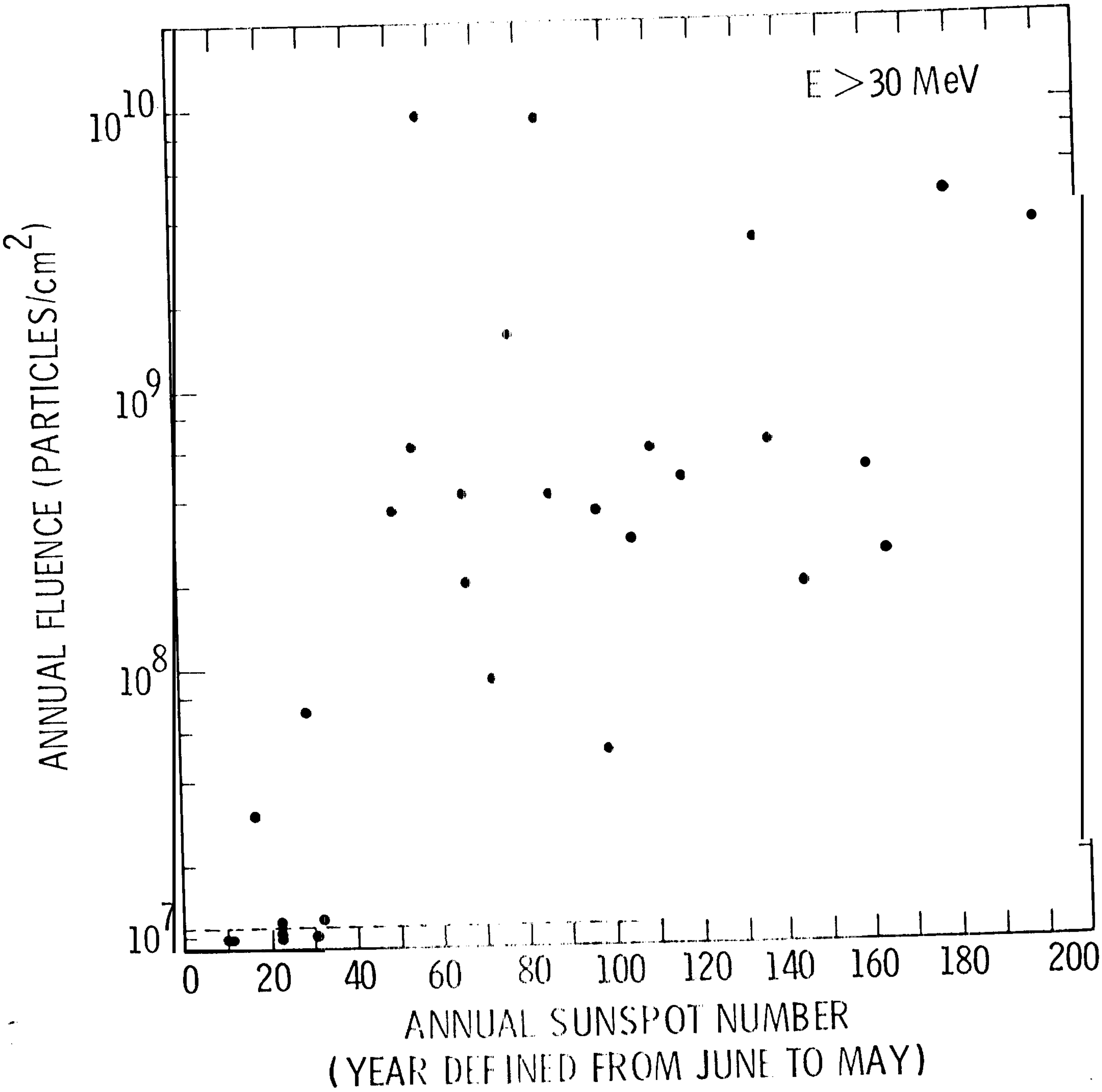




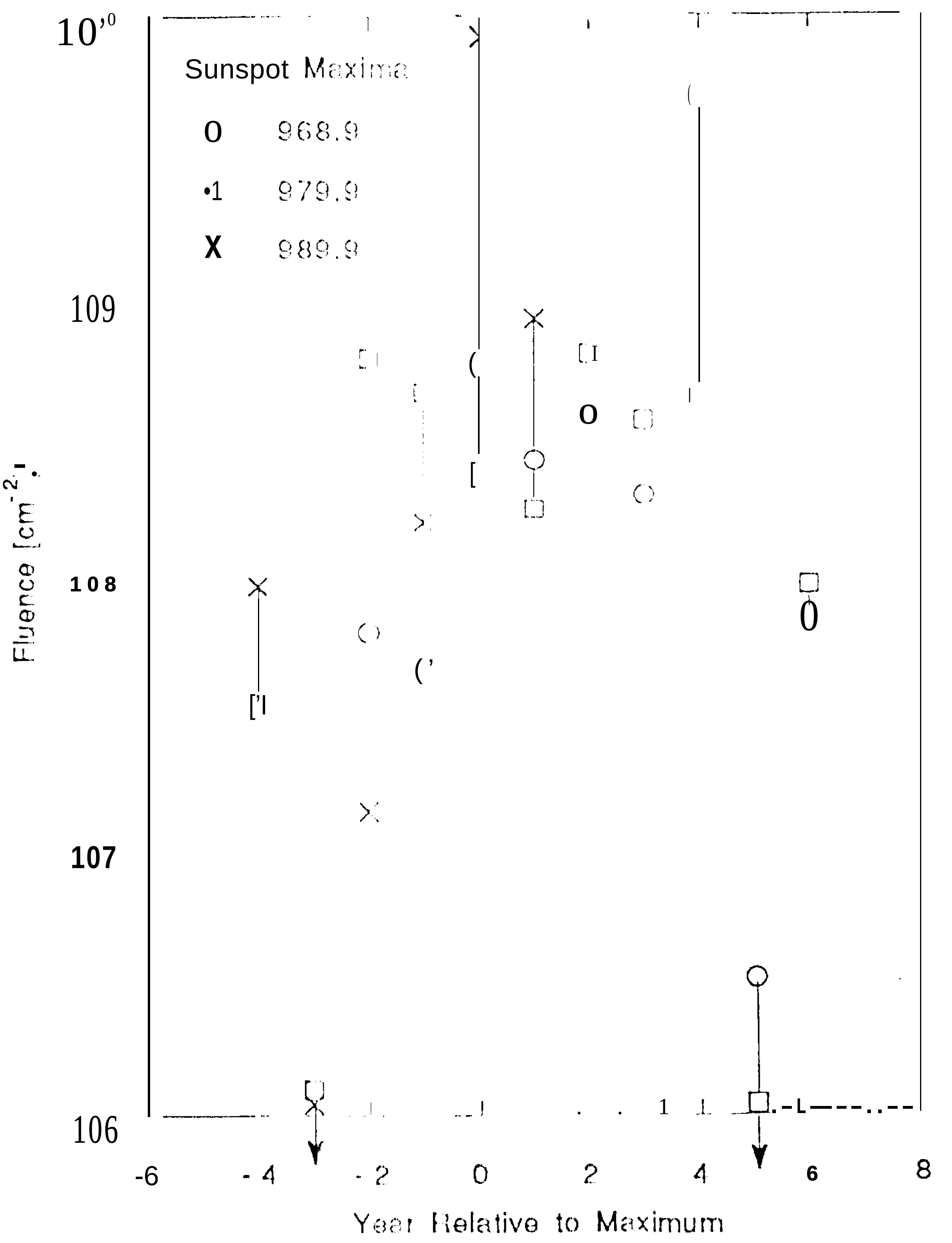
Fraction in 100 km/see intervals
0.2
.15
0.1
.05
0.00
1980, 1984 to 1989
936 Measurements
Median
Avg.
100
200
300
400
500
600
800
900
1000
1200
Speed [km/sec]


Mach 1 Rs
Mach 2 Rs
80
70
60
50
40
30
20
10
0
Mach Rs
400
600
800
1000
1200
1400
1600
CME velocity

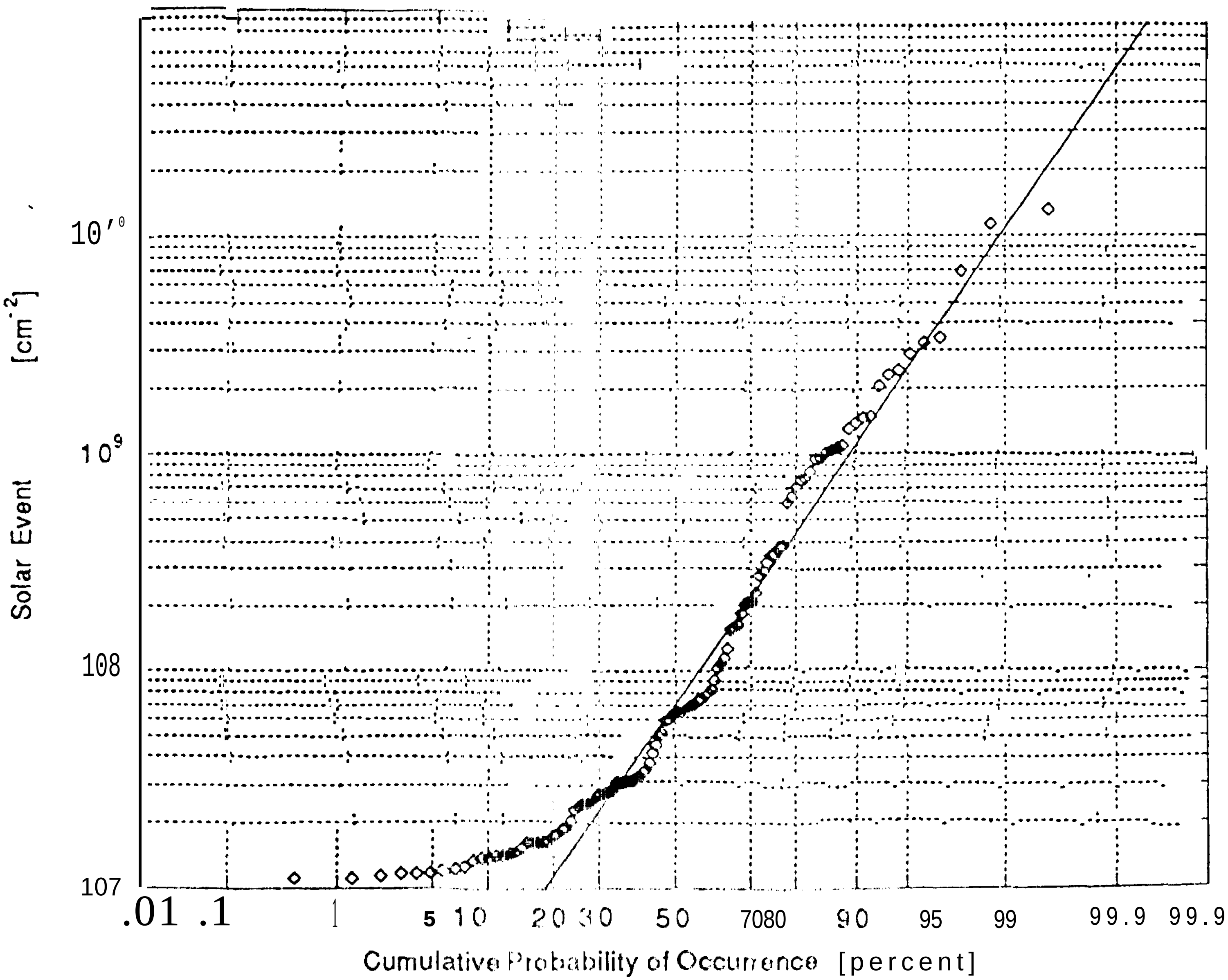
ANNUAL. F'I?C')1ON FLUENCE
vs. SUNSPOTNUMBER



YEARLY FLUENCES (>30 MeV)



Event Integrated Fluences
active Sun, :19631991., E > 10 Mev



Mission Fluence Probability
E > 10 Mev